

Associated Higgs Production in CP-violating supersymmetry: probing the ‘open hole’ at the Large Hadron Collider

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Abstract

A benchmark CP -violating supersymmetric scenario (known in the literature as ‘CPX-scenario’) is studied in the context of the Large Hadron Collider (LHC). It is shown that the LHC, with low to moderate accumulated luminosity, will be able to probe the existing ‘hole’ in the m_{h_1} - $\tan \beta$ plane, which cannot be ruled out by the Large Electron Positron Collider data. This can be done through associated production of Higgs bosons with top quark and top squark pairs leading to the signal *dilepton + ≤ 5 jets (including 3 b -jets) + missing p_T* . Efficient discrimination of such a CP -violating supersymmetric scenario from other contending ones is also possible at the LHC with a moderate volume of data.

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1 Introduction

One of the main motivations for suggesting supersymmetry (SUSY) is to remove the fine-tuning problem in the Higgs sector of the standard model. The condition of holomorphicity of the superpotential requires two Higgs doublets in the minimal SUSY extension of the standard model (SM). There the Higgs sector has a larger particle content than the SM, and the physical states in this sector comprise two neutral scalars, one pseudoscalar and one charged Higgs boson. Finding the signatures of these scalars is thus inseparably linked with the search for SUSY at the upcoming Large Hadron Collider (LHC).

Prior to the LHC several Higgs search experiments have yielded negative results. The strongest lower bound on the smallest Higgs mass (m_h) from the Large Electron Positron Collider (LEP) is $m_h > 114.4$ GeV [1, 2]. This limit is valid for a SM like Higgs as well as for the lightest neutral Higgs boson in the minimal supersymmetric standard model (MSSM) in the decoupling limit i.e. the limit in which the masses of all other scalars in the Higgs sector become very large. Although smaller values of m_h are allowed away from the decoupling limit, the lower bound on its mass is approximately the Z -mass. However, when the Higgs sector inherits some CP -violating phase through radiative corrections [3, 4], the above limit ceases to be valid. Our discussion is centred around such situations.

It is well-known by now that lower bound on the mass of the lightest Higgs boson of the CP -conserving MSSM from LEP [2] can be drastically reduced or even may entirely vanish if non-zero CP -violating phases are allowed [5]. This can happen through radiative corrections to the Higgs potential, whereby the phases, if any, of the Higgsino mass parameter μ and the trilinear soft SUSY breaking parameter A enter into the picture. As a result of the CP -violating phase, the neutral spinless states are no more of definite parity, and their couplings to gauge bosons as well as fermions are thus modified, depending on the magnitude of the phases. Thus there are three neutral states h_i ($i=1,2,3$); the collider search limits for all of them are modified since the squared amplitudes for production via WW , ZZ and $q\bar{q}$ couplings for all of them now consist of more than one terms. Mutual cancellation among such terms can take place in certain regions of the parameter space, thus resulting in reduced production rates and consequent weakening of mass limits at collider experiments.

For example, in the context of a benchmark CP -violating scenario (often called the CPX scenario in the literature [5]), it has been found that m_{h_1} as low as 50 GeV or even smaller, cannot be ruled out by the final LEP data for low and moderate values of $\tan\beta$, where h_1 is the lightest neutral Higgs, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. In other words, a ‘hole’ is found to exist in the m_{h_1} - $\tan\beta$ parameter space covered by the LEP searches, the underlying reason being the reduction in the coupling ZZh_1 due to the CP -violating phase(s),

as mentioned above. Moreover, complementary channels such as $e^+e^- \rightarrow h_1 h_2$, suffer from coupling as well as phase-space suppression within this ‘hole’, thus making it inaccessible to LEP searches. The existence of this hole has been confirmed by the analyses of the LEP data by different experimental groups [2, 5, 6], although people are not unanimous about the exact span of the hole.

The next natural step is to assess the prospect of closing the hole at Tevatron Run II or the LHC. The existing analysis on this [7], however, focuses on the discovery channels based on the conventional Higgs production and decay mechanisms employed in the context of the SM. It has been noted that although the hadron colliders can probe most of the parameter space of the CPX scenario and can indeed go beyond some regions of the parameter space scanned by the LEP searches, the lightest Higgs boson within the aforementioned hole may still escape detection. This is because not only ZZh_1 but also the $WW h_1$ and $t\bar{t}h_1$ couplings tend to be very small within this hole. On the other hand, the relatively heavy neutral Higgs bosons $h_{2,3}$ couple to W , Z and t favourably, but they can decay in non-standard channels, thus requiring a modification in search strategies. The work [8] which has compiled possible signals of the CPX scenario at the LHC is also restricted to the production of h_i ($i=1,2,3$) bosons in SM-like channels. However, it looked into more decay channels of the h_i bosons thus produced. It has been henceforth concluded that parts of the holes in the M_H^+ - $\tan\beta$ or the m_{h_1} - $\tan\beta$ parameter space can be plugged, although considerable portions of the hole, especially for low $\tan\beta$, may escape detection at the LHC even after accumulating 300 fb^{-1} of integrated luminosity.

Thus it is important to look for other production channels for the scalars in the CPX region, especially by making use of the couplings of h_1 with the sparticles. It is gratifying to note in this context that the $\tilde{t}_1 \tilde{t}_1^* h_1$ coupling, where \tilde{t}_1 is the lighter top squark, indeed leads to such a discovery channel, in cases where the $t\bar{t}h_1$ and W - W - h_1 , Z - Z - h_1 couplings are highly suppressed. In fact it has been noted that in a general CP -violating MSSM, the cross section of $\tilde{t}_1 \tilde{t}_1^* h_1$ production could be dramatically larger than that obtained by switching off the CP -violating phases [9]. Since the trilinear SUSY breaking parameter A_t is necessarily large in the CPX scenario, \tilde{t}_1 tends to be relatively light and may be produced at the LHC with large cross section. As a bonus, both h_2 and h_3 also couple favourably to the $t\bar{t}$ pair and can add modestly to the signal although by themselves they fail to produce a statistically significant signal. In this work we investigate the implications of these couplings at the LHC, by concentrating on a specific signal arising from the associated production of the neutral Higgs bosons with a top-pair or a pair of lighter stop squarks.

Our task, however, does not end here. While we wish to extract information on the neutral Higgs sector in the CPX scenario, other SUSY processes driven by other particles in the spectrum may yield the same final state. To make sure that one is indeed looking at the Higgs sector, one needs to isolate the Higgs-induced channels, and find

event selection criteria to not only reduce the SM backgrounds but also ensure that the canonical SUSY channels do not overwhelm the Higgs signatures. In our analysis, we first introduce suitable criteria which will suppress the SM background compared to the total SUSY contribution in CPX. Next, we suggest additional discriminators for further filtering out the contributions of the lightest Higgs (h_1) from other SUSY channels. We finally show that if nature prefers the SM alone with $m_h \geq 114.4$ GeV, or, alternatively, CP -conserving SUSY, the proposed signal would indeed be much smaller if our selection criteria are imposed.

The paper is organised as follows. In Section 2 we discuss the basic inputs of the CPX scenario, the resulting mass spectrum and other features they lead to. All of our subsequent numerical analysis would be in this framework where we also use the alternative expression CPV-SUSY to mean the CPX-scenario. In section 3 we set out to define the proposed signal, devise the event selection criteria to reduce both SM and residual SUSY backgrounds and fake events, and present the final numerical results. We summarise and conclude in section 4.

2 The CPX Model: values of various parameters

As indicated in the Introduction, we adopt the so called CPX scenario in which the LEP analyses have been performed. It has been observed [3, 4] that the CP -violating quantum effects on the Higgs potential is proportional to $Im(\mu A_t)/M_{SUSY}^2$, where A_t is the trilinear soft SUSY breaking parameter occurring in the top squark mass matrix, and M_{SUSY} is the characteristic SUSY breaking scale, being of the order of the third generation squark masses. With this in mind, a benchmark scenario known as CPX was proposed [5] and its consequences were studied [[10]–[23]] in some of which steps are suggested for closing the aforementioned ‘hole’ [24, 25, 26]. In this scenario, the effects of CP -violation are maximized. The corresponding inputs that we adopt here are compatible with the “hole” left out in the analysis.

$$\begin{aligned} m_{\tilde{t}} = m_{\tilde{b}} = m_{\tilde{\tau}} = M_{SUSY} &= 500 \text{ GeV}, & \mu &= 4M_{SUSY} = 2 \text{ TeV} \\ |A_t| = |A_b| &= 2M_{SUSY} = 1 \text{ TeV}, & arg(A_{t,b}) &= 90^\circ \\ |m_{\tilde{g}}| &= 1 \text{ TeV}, & arg(m_{\tilde{g}}) &= 90^\circ \\ M_2 = 2M_1 &= 200 \text{ GeV}, & \tan \beta &= 5 - 10 \end{aligned}$$

where the only departure from reference [7] lies in a small tweaking in the mass ratio of the $U(1)$ and $SU(2)$ gaugino masses M_1 and M_2 , aimed at ensuring gaugino mass unification at high scale. It has been checked that this difference does not affect the Higgs production or the decay rates [27]. The presence of a relatively large A_t ensures that one of the top squarks will be relatively light. The value of the top quark mass

has been taken to be 175 GeV⁵.

It is to be noted that the first two generation sfermion masses must be kept sufficiently heavy so that the stringent experimental bound (for example, the electric dipole moment of the neutron) is satisfied. Here we have not considered possible ways of bypassing such bounds, and set the masses of the first two sfermion families at 10 TeV. Thus our analysis is based on the mass spectrum showed in Table 1.

m_{h_1}	m_{h_2}	m_{h_3}	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$	$m_{\chi_1^0}$	$m_{\chi_2^0}$	$m_{\chi_1^\pm}$
48.9	103.3	135.7	322.0	664.0	476	527	99.6	198.4	198.4

Table 1: Physical masses (in GeV) of neutral Higgs bosons, squarks and lighter gauginos in the CPX scenario with $\tan\beta=5$ and $m_{H^\pm}=130$ GeV.

The specific choice of m_{H^\pm} is made to obtain the mass of the lightest Higgs boson within the LEP-hole in m_{h_1} - $\tan\beta$ space. It should be noted that such a choice makes the remaining two neutral Higgs bosons not so heavy either. This kind of a situation has a special implication in CPV-MSSM, namely, all the neutral Higgs bosons can be produced in association with a \tilde{t}_1 pair. Such production is kinematically suppressed in the CP -conserving case due to the lower bound on m_h .

The CPX set of parameters listed above constitutes our benchmark point number 1 (BP1) in the detailed analysis to be undertaken in the next section. We list at the end of that section the final results corresponding to six more benchmark points within the hole unprobed by current data. These points are denoted by BP2 - BP7.

3 Signals at the LHC

Since, in CPX-SUSY the VVh_1 ($V=W, Z$) and $t\bar{t}h_1$ interactions are suppressed for the lightest neutral scalar(h_1), we shall have to think of some alternative associate production mechanism at the LHC. One possibility is to consider the associated production of h_1 with a pair of lighter stops. The large value of A_t is encouraging in this respect. In addition, since the point CPX yields a not-so-high value of the lighter stop mass, this production mechanism is kinematically quite viable.

The cross sections for different supersymmetric associated production processes are computed with **CalcHEP** [28] (interfaced with the program **CPSuperH** [29, 30]) and listed in Table 2. As one can see, while a substantial production rate is predicted for h_1

⁵The frequent shift in the central value of m_t , coming from Tevatron measurements, causes the size of the hole to change, although its location remains the same. However, there is little point in worrying about this uncertainty, since the very quantum corrections which are at the root of all CP -violating effects in the Higgs sector are prone to similar, if not greater, theoretical uncertainties.

associated with a pair of \tilde{t}_1 , the corresponding cross sections for h_2 and h_3 are smaller by two orders of magnitude. This is not only because of phase space suppression for the latter at the CPX point, but also due to the conspiracy of a number of terms in the effective interaction involved. Table 2 also reveals a complementary feature in Higgs production in association with a pair of top quarks, the underlying reason being again the multitude of terms that enters into the squared amplitudes, and the provision of their mutual cancellation in the CPX scenario. Thus we can identify, for the given set of input parameters, $\tilde{t}_1\tilde{t}_1^*h_1$ and $t\bar{t}h_{2,3}$ as the production processes that can be potentially useful in closing the hole in the parameter space.

Also indicated in Table 2 is the gluino pair production cross section in the CPX scenario for $m_{\tilde{g}}=1$ TeV which is a CPX input indicated earlier in this section. Later in this section, we shall explain how this process could affect our signal.

$\sigma_{\tilde{t}_1\tilde{t}_1^*h_1}$	$\sigma_{\tilde{t}_1\tilde{t}_1^*h_2}$	$\sigma_{\tilde{t}_1\tilde{t}_1^*h_3}$	$\sigma_{t\bar{t}h_1}$	$\sigma_{t\bar{t}h_2}$	$\sigma_{t\bar{t}h_3}$	$\sigma_{\tilde{g}\tilde{g}}$
440	6	4	8	198	135	134

Table 2: Production cross sections (in fb) at lowest-order computed with **CalcHEP** interfaced with **CPsuperH** for different signal processes at the LHC in the CPX scenario and for the spectrum of Table 1. **CTEQ6L** parton distribution functions are used and the renormalization/factorization scale is set to $\sqrt{\hat{s}}$.

The branching fractions of the lighter scalar top and the lightest neutral Higgs boson plays a crucial role in selecting the viable modes in which the signal for CPV-SUSY can be looked for. In Table 3 we present the relevant branching fractions, keeping in mind that new final states emerge whenever the branching fraction for a heavier neutral scalar decaying into two lighter ones is of sizable magnitude. In any case, it is interesting to note that not only the lightest Higgs h_1 but also h_2 and h_3 could play significant roles in signals of the Higgs sector in the CPX scenario, given the possibility of all of them being rather light.

$\text{Br}(\tilde{t}_1 \rightarrow b\chi_1^+)$	$\text{Br}(\tilde{t}_1 \rightarrow t\chi_1^0)$	$\text{Br}(h_1 \rightarrow b\bar{b})$	$\text{Br}(h_2 \rightarrow h_1h_1)$	$\text{Br}(h_3 \rightarrow h_1h_1)$	$\text{Br}(\tilde{g} \rightarrow t\bar{t})$
0.81	0.19	0.91	0.71	0.82	0.16

Table 3: Branching fractions for lighter top squark, the neutral Higgs bosons and gluino in the CPX scenario.

Before we enter into the discussion of our specifically chosen signal, let us mention that, in this study, **CalcHEP** (interfaced to the program **CPsuperH**) has also

been used for generating parton-level events for the relevant processes. The standard `CalcHEP`–`PYTHIA` interface [31], which uses the SLHA interface [32] was then used to pass the `CalcHEP`-generated events to `PYTHIA` [33]. Further, all relevant decay-information are generated with `CalcHEP` and are passed to `PYTHIA` through the same interface. All these are required since there is no public implementation of CPV-MSSM in `PYTHIA`. Subsequent decays of the produced particles, hadronization and the collider analyses are done with `PYTHIA` (version 4.610).

We used CTEQ6L parton distribution function (PDF) [34, 35]. In `CalcHEP` we opted for the lowest order α_s evaluation, which is appropriate for a lowest order PDF like CTEQ6L. The renormalization/factorization scale in `CalcHEP` is set at \sqrt{s} . This choice of scale results in a somewhat conservative estimate for the event rates.

As discussed earlier, the processes of primary importance for the present study are $pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$ and $pp \rightarrow t \bar{t} h_{2,3}$. At the parton level, the lightest Higgs and both top quarks (or top squarks) dominantly decay to b quarks. For our signal, the associated W 's (or charginos) produced in the decay of t (or \tilde{t}_1) are required to decay into leptons with known or calculable branching ratios. These decays lead to a final state with *four* b -quarks along with other SM particles. In addition, the large branching ratios for $h_{(2,3)} \rightarrow h_1 h_1$ can make the modest contributions from the $t \bar{t} h_{(2,3)}$ particularly rich in final state b 's, which, with a finite b -tagging efficiency, can provide a combinatoric factor of advantage to us.

However, although h_1 decays dominantly into $b \bar{b}$, our simulation reveals that in a fairly large fraction of events both the b -quarks do not lead to sufficiently hard jets with reasonable b -tagging efficiency. This is because of the lightness of h_1 in this scenario. To illustrate this, we present in Figure 1 the ordered p_T distributions for the four parton-level b -quarks in the signal from $\tilde{t}_1 \tilde{t}_1^* h_1$. It is clear from this figure that the b -quark with the lowest p_T in a given event is often below 40 GeV or thereabout, which could have ensured a moderate tagging efficiency ($\geq 50\%$). This forces us to settle for three tagged b -jets in the final state, and look for

$$3 \text{ tagged } b\text{-jets} + \text{dilepton} + \text{other untagged jets} + \text{missing } p_T.$$

Later in this section we will demonstrate that this feature is retained under a realistic situation, i.e. on inclusion of hadronization.

We have used PYCELL, the toy calorimeter simulation provided in `PYTHIA`, with the following criteria:

- the calorimeter coverage is $|\eta| < 4.5$ and the segmentation is given by $\Delta\eta \times \Delta\phi = 0.09 \times 0.09$ which resembles a generic LHC detector
- a cone algorithm with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$ has been used for jet finding
- $p_{T,min}^{jet} = 30$ GeV and jets are ordered in p_T
- leptons ($\ell = e, \mu$) are selected with $p_T \geq 30$ GeV and $|\eta| \leq 2.5$

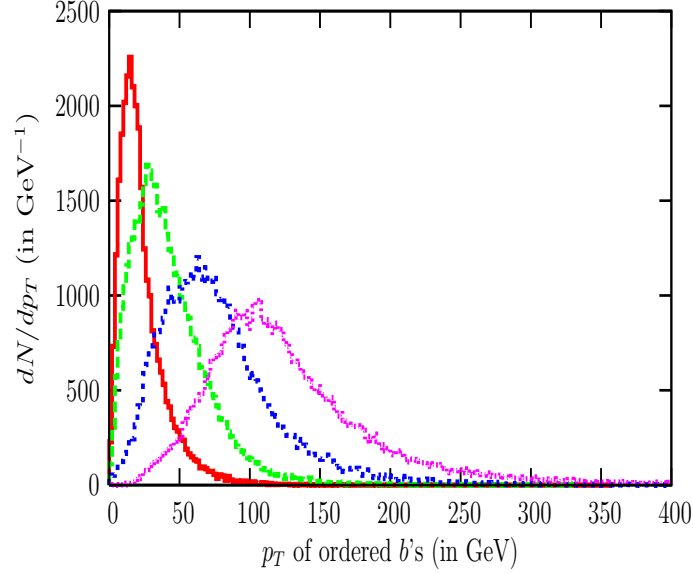


Figure 1: Ordered p_T distributions for all four parton level b -jets arising from the decays of \tilde{t}_1 , \tilde{t}_1^* and h_1 in $\tilde{t}_1\tilde{t}_1^*h_1$ production.

- no jet should match with a hard lepton in the event

In addition, the following set of basic (standard) kinematic cuts is incorporated throughout our analysis:

$$p_T^{j1,2} \geq 50 \text{ GeV} \quad p_T^{j3} \geq 40 \text{ GeV} \quad |\eta|_{j,\ell} \leq 2.5$$

$$\Delta R_{\ell j} \geq 0.4 \quad \Delta R_{\ell\ell} \geq 0.2$$

where $\Delta R_{\ell j}$ and $\Delta R_{\ell\ell}$ measure the lepton-jet and lepton-lepton isolations respectively, with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, $\Delta\eta$ being the pseudo-rapidity difference and $\Delta\phi$ being the difference in azimuthal angle for the adjacent leptons and/or jets. Since efficient identification of the leptons is crucial for our study, we required, on top of above set of cuts, that hadronic activity within a cone of $\Delta R = 0.2$ between two isolated leptons should be minimum with $p_T^{jet} < 10 \text{ GeV}$ in the specified cone. Throughout the analysis we have assumed that a b -jet with $p_T^{jet} > 40 \text{ GeV}$ can be tagged with 50% probability. In addition, as we shall see below, some further kinematic cuts are necessary to make the proposed signal stand out.

Below the contributions to the final state from different scenarios are discussed:

- Contributions coming from the CPV-SUSY scenario and comprised of $pp \rightarrow \tilde{t}_1\tilde{t}_1^*h_1, t\bar{t}h_{2,3}$ and $pp \rightarrow \tilde{g}\tilde{g}$ where m_{h_1} could escape the LEP bound and can be as light as 50 GeV for low to moderate $\tan\beta$.
- If nature is supersymmetric but conserves CP (CPC-SUSY), contributions could dominantly come from $pp \rightarrow t\bar{t}h$ and $\tilde{g}\tilde{g}$, where the appropriate LEP bound

hold for m_h . Obviously, m_h now has to be much larger than that in the CPV-SUSY case. For our study, this constitutes a crucial difference between these two scenarios for a given set of masses for the gluino and the lighter top squark.

- If the SM is the only theory relevant for the LHC, then the dominant signal process is from $pp \rightarrow t\bar{t}H$, where H is the SM Higgs boson for which the LEP bound of $m_H > 114.4$ GeV is valid.
- The SM contributions coming from $pp \rightarrow t\bar{t}, t\bar{t}Z, t\bar{t}b\bar{b}$ ⁶ etc., which appear as “common background” for all the above three situations.

Note that in first three scenarios the contributing processes all involve characteristic masses and/or couplings either in the production or in the subsequent cascades. Thus observations made there directly carry crucial information on the scenario involved and hence may help discriminate the same from the others.

The SM contributions in the last item of the above list are not sensitive, in any relevant way, to the details of any new physics scenarios. Thus they appear as universal backgrounds to the chosen signal coming from all of the other three scenarios. The major sources in this category are (i) $t\bar{t}$ production with a c -jet from QCD radiation mistagged as the third b -jet (we assume mistagging probability to be 1/25 [37]), (ii) $t\bar{t}b\bar{b}$ production where the semileptonic decays of the t quarks produce the hard, isolated OSD pair and (iii) $t\bar{t}Z$ production where the Z decays into b -quarks and the leptons come from t -decay.

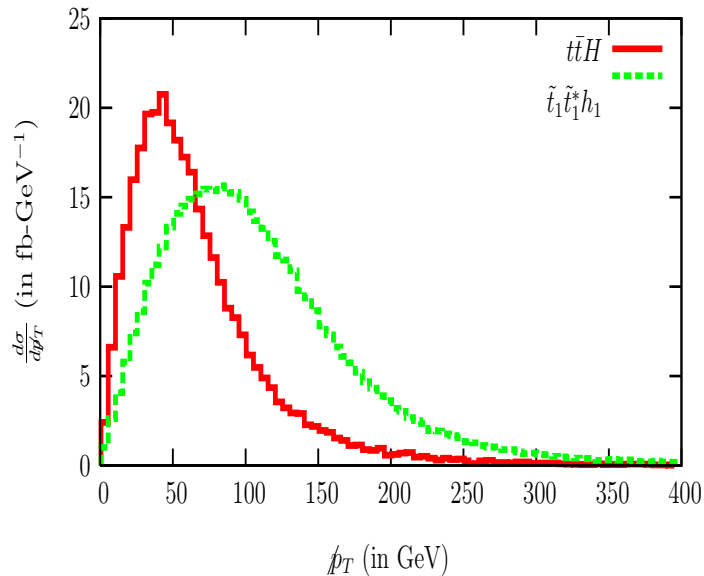


Figure 2: $/p_T$ distribution with arbitrary normalisation for the CPV-SUSY $\tilde{t}_1\tilde{t}_1^*h_1$ and the SM $t\bar{t}H$ background.

⁶We thank Manas Maity for estimating this background using the calculation reported in [36].

The most effective way to reduce the contribution from $t\bar{t}H$ in the SM (with $m_H=120$ GeV) is found to come from the missing p_T distributions. In Figure 2, we present the $/p_T$ distribution for our proposed signal, arising from the associated lightest Higgs production along with a stop squark pair. Since the plots demonstrate that the CPX signal contains more events with $/p_T$ on the higher side (due to the massive lightest neutralino pair in the final state), an appropriate $/p_T$ -cut is clearly useful. Therefore, we have subjected our generated events to the additional requirement

$$\cancel{p}_T \geq 110 \text{ GeV}.$$

This is added to the basic cuts listed earlier, yielding an overall efficiency factor denoted here by ϵ which contains the effects of all cuts described so far as well as those to be mentioned later in the text. The finally important numbers for the signal and any of the faking scenarios are thus given by the quantity $\sigma \times \epsilon$, σ being the cross section for the aforementioned final state without any cuts.

In case the SM is the only relevant theory for such final states at the LHC, $pp \rightarrow t\bar{t}H$ as well as the sources of ‘common backgrounds’ will contribute to our final state. In this, one will have to take $m_H \geq 114.4$ GeV to be consistent with the experimental observations. The missing- p_T cut of $\cancel{p}_T > 110$ GeV effectively reduces events of both these types. Thus having enough signal events above the standard model predictions is ensured in this search strategy.

However, the same final state can have strong contributions from strong production such as $pp \rightarrow \tilde{g}\tilde{g}$, followed by a cascade like

$$\tilde{g} \rightarrow t\bar{t}_1^* \rightarrow t\bar{t}\chi_1^0 \rightarrow b\bar{b}W^+W^-\chi_1^0$$

While these may add to the signal strength, there is always the possibility that the fluctuation in the gluino-induced events owing to the uncertainties of strong interaction will tend to submerge the channels of our real interest, namely, the associated production of the neutral Higgs bosons. In the same way, contributions from strong processes may also fake the proposed signals in CP -conserving SUSY. The next task, therefore, is to devise acceptance criteria to avoid such fake events. We take as representative the gluino pair production process as the interfering channel, the contributions from squarks being small at the corresponding parameter region.

The first point to note here is that the contributions from strong processes leading to this final state usually have a higher jet multiplicity than in our case. This is evident from Figure 3 where we present the jet-multiplicity distribution at the CPX point. While the contributions from associated Higgs production peak at four jets, the overall peak lies at seven. This immediately suggests jet multiplicity as a useful acceptance criterion here, and thus we demand $n_j \leq 5$, thereby reducing considerably the artifacts of strong processes.

There are other SUSY processes which may tend to obfuscate the presence of a rather light Higgs boson. For example, similar final states may arise from processes

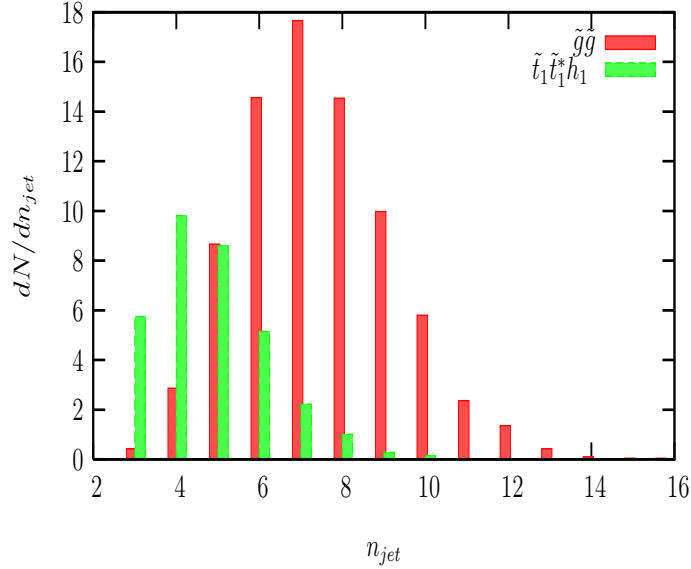


Figure 3: Final state jet multiplicity distributions (with arbitrary normalisation) arising from $\tilde{t}_1 \tilde{t}_1^* h_1$ (in green) and $\tilde{g} \tilde{g}$ (in red) in the CPV-SUSY scenario.

like $pp \rightarrow \tilde{b}_1 \tilde{b}_1^* h_1$, where the \tilde{b}_1 's decay into a b -quark and the second lightest neutralino. The latter, in turn, decays into two leptons and the lightest supersymmetric particle (LSP). The number of such events, however, is negligible due to a highly suppressed $\tilde{b}_1 \tilde{b}_1^* h_1$ coupling at moderate to low $\tan \beta$ values, i.e., the range of $\tan \beta$ answering to the CPX scenario. In case of faking in a CP -conserving SUSY spectrum with high $\tan \beta$ ($\simeq 40$ or so), one has to study independently the $b\bar{b}$ and $\tau^+ \tau^-$ interactions, for example, in the vector boson fusion channel [38, 39, 40, 41], where the values of the parameters can be established as different from those giving rise to the ‘hole’ in the CPX case.

The strong cascades, however, continue to remain problematic even after imposing the jet multiplicity cut, since the production cross-sections are quite large and the multiplicity cut removes only about half of the events. The next suggestion thus is to use those characteristics of the events that reflect the mass (1 TeV) of the gluino in the CPX case. The obvious distributions to look at are those of the transverse momenta of the various jets, for the final states arising from associated Higgs production vis-a-vis strong processes. It is natural to expect that jets originating in gluino decays will have harder p_T^{jet} distributions compared to those coming from the associated Higgs productions. This is obvious on comparing the left and right panels of Figure 4 which shows the ordered p_T -distributions of jets arising from $\tilde{t}_1 \tilde{t}_1^* h_1$ and $\tilde{g} \tilde{g}$ productions in this scenario.

Thus we further impose an upper cut on p_T^{jet} , viz., $p_T^{jet} \leq 300$ GeV, which ‘kills’ the

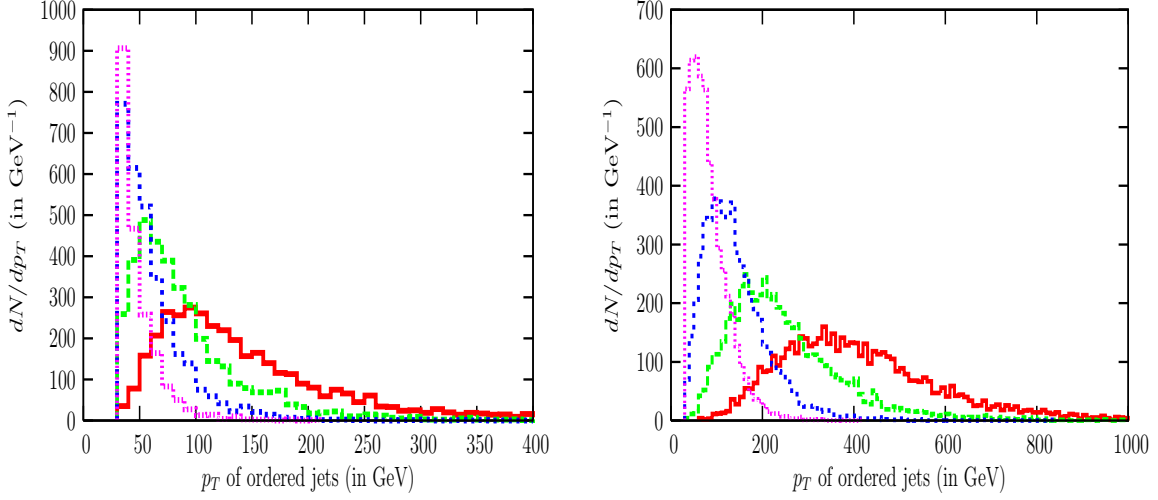


Figure 4: Ordered p_T^{jet} distributions in CPV-SUSY scenario: $\tilde{t}_1 \tilde{t}_1^* h_1$ (left) and $\tilde{g} \tilde{g}$ (right)

more energetic jets from the strong production process. Together with the stipulated upper limit on jet multiplicity, this helps in enhancing the share of the associated Higgs production processes in the final state under investigation. Thus the effects of the \cancel{p}_T , multiplicity and maximum p_T^{jet} cuts all enter into the quantity ϵ determining the final rates after all the event selection criteria are applied.

Now we are in a position to make a comparative estimate of the contributions to *dilepton + ≤ 5 jets including three tagged b -jets + \cancel{p}_T* from the various scenarios, and assess the usefulness of this channel in extracting the signature of a CP -violating SUSY scenario with light neutral scalars. Such an estimate is readily available from Tables 4 and 5.

Table 4 contains the contributions to the aforesaid final state from the CPX benchmark point 1 (BP1), CP -conserving SUSY and a standard model Higgs boson of masses 117 and 120 GeV respectively. These are *over and above the ‘common backgrounds’* which are listed in Table 5. In each case, the main contributing processes and the corresponding hard cross-sections are shown. Also displayed are the final event rates once the various cuts are imposed, where the difference made by the upper cut on p_T^{jet} is clearly brought out.

As far as the choice of parameters in CP -conserving SUSY is concerned, we have used the same values of the gluino and first two generations of squark masses as in the CPX point. It is expected that any departure in the strong sector masses from those corresponding to the hole in the CPX case will be found out from variables such as the energy profile of jets, if any signal of SUSY is seen at the LHC. Thus other regions of the MSSM parameter space are unlikely to fake the signals of CP -violating situation. The value of $\tan \beta$ is also kept at the region allowed by the CPX hole, and any departure from this region in a faking MSSM scenario has to show up in the branching ratios

Scenarios	Processes	Hard Cross-sections in fb without cut	$\sigma \times \epsilon$ in fb without (with)upper p_T^{jet} cut	Final number at $\mathcal{L}=30 \text{ fb}^{-1}$
CPV	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	440	0.5(0.38)	15(11)
SUSY	$pp \rightarrow t\bar{t}h_2$	197	0.23(0.16)	7(5)
	$pp \rightarrow t\bar{t}h_3$	135	0.23(0.17)	7(5)
	$pp \rightarrow \tilde{g}\tilde{g}$	134	0.70(0.167)	21(5)
CPC-	$pp \rightarrow t\bar{t}h$	330	0.33(0.27)	10(8)
SUSY	$pp \rightarrow CPC(\tilde{g}\tilde{g})$	134	0.33(0.07)	10(2)
SM	$pp \rightarrow SM(t\bar{t}H)$	340	0.33(0.27)	10(8)

Table 4: Event rates for the CPX point, CP -conserving SUSY and the standard model with same mass spectrum as CPX except for $m_{h,H} = 117, 120$ GeV for latter two cases respectively.

for $h_1 \rightarrow b\bar{b}, \tau^+\tau^-$, using the supplementary data on the vector boson fusion channel. Finally, although some difference from the rates shown in Table 4 for CP -conserving SUSY can in principle occur due to different values of the lighter stop mass, the overall rates are not significantly different, so long as stop squark decays dominantly into either $b\chi_1^+$ or $t\chi_1^0$. Thus the choice of the CP -conserving SUSY parameters in Table 4 can be taken as representative. We checked that for smaller choice of \tilde{t}_1 mass also and the number is still smaller than CPX contribution.

It is easy to draw one's own conclusion from these two tables about the viability of the suggested search strategy. With the selection criteria proposed in this paper (without the upper cut on jet p_T) the size of the signal (50 events) from the dominant processes in CPV-SUSY for only 30 fb^{-1} of integrated luminosity easily dwarfs the common SM background (13 events). Moreover, the signal size is much larger than that in the CPC scenario (with comparable squark and gluino masses) or in the SM. Thus, important hints regarding the existence of new physics and its nature will be available at this stage (we assume that the gluino mass and some other important parameters will be determined from complimentary experiments). The presence of the lightest Higgs boson and its not so heavy mates becomes clear after the upper cut on

Models	Processes	Hard Cross-sections in fb (without cut)	$\sigma \times \epsilon$ in fb without (with)upper p_T^{jet} cut	Final number at $\mathcal{L}=30 \text{ fb}^{-1}$
Common Background	$(pp \rightarrow t\bar{t})$	3.7×10^5	0.1(0.1)	3(3)
	$(pp \rightarrow t\bar{t}Z)$	370	0.03(0.03)	1(1)
	$(pp \rightarrow t\bar{t}b\bar{b})$	831	0.3(0.3)	9(9)

Table 5: Event rates for the ‘common background’ with and without the upper cut on p_T^{jet} .

p_T since nearly 75% of the new physics events are now induced by them. Clearly, even after imposing the upper cut on p_T^{jet} , the signals can rise above the SM backgrounds at more than 5σ level within a moderate integrated luminosity like 30fb^{-1} . This can be further magnified with the accumulation of luminosity. On the other hand, it is not too optimistic to assume that important hints will be available with only 10 fb^{-1} of integrated luminosity.

Parameters	BP2	BP3	BP4	BP5	BP6	BP7
$\tan \beta$	5.0	7.0	7.0	6.0	5.0	7.0
m_{h_1} (GeV)	40.5	40.4	49.0	45.1	30.0	30.0

Table 6: Benchmark points within the LEP-hole in m_{h_1} - $\tan \beta$ plane.

Before we end this discussion, we show the viability of this signal in other regions of the CPX hole. It has already been noted in the literature that the size and the exact location of the hole in the parameter space depend on the method of calculating the loop corrections [30, 42, 43]. However, the calculations agree qualitatively and confirm the presence of the hole. To be specific we have chosen points from the hole as presented by [6].

In Table 6 we present different sets of values of $\tan \beta$ and m_{h_1} , keeping the other parameters fixed at their CPX values. These correspond to six different regions of the LEP hole and are termed as benchmark points 2 -7 (BP2 - BP7), all within the hole. The analysis for each of these points is an exact parallel of that already presented for

the first benchmark point. We have computed the generic sensitivity of LHC to the ‘hole’ corresponding to each of these benchmark points, the results being summarised in Table 7. It is clear from this Table that we always have enough events (> 15) in our attempt to probe the LEP-hole even with an integrated luminosity of 30 fb^{-1} . As the luminosity accumulates a statistically significant signal will be obtainable from any corner of this hole.

Bench Marking points	Processes	Cross -section in fb	$\sigma \times \epsilon$ in fb with upper p_T^{jet} cut	Total $\sigma \times \epsilon$ in fb	Events at $\mathcal{L}=30$ fb^{-1}
BP2	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	560	0.47	0.67	20
	$pp \rightarrow t\bar{t}h_2$	180	0.10		
	$pp \rightarrow t\bar{t}h_3$	145	0.10		
BP3	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	437	0.37	0.63	19
	$pp \rightarrow t\bar{t}h_2$	180	0.10		
	$pp \rightarrow t\bar{t}h_3$	195	0.16		
BP4	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	350	0.34	0.60	18
	$pp \rightarrow t\bar{t}h_2$	135	0.10		
	$pp \rightarrow t\bar{t}h_3$	178	0.16		
BP5	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	422	0.37	0.69	21
	$pp \rightarrow t\bar{t}h_2$	154	0.13		
	$pp \rightarrow t\bar{t}h_3$	167	0.19		
BP6	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	760	0.59	0.88	26
	$pp \rightarrow t\bar{t}h_2$	170	0.11		
	$pp \rightarrow t\bar{t}h_3$	170	0.18		
BP7	$pp \rightarrow \tilde{t}_1 \tilde{t}_1^* h_1$	590	0.48	0.74	22
	$pp \rightarrow t\bar{t}h_2$	100	0.06		
	$pp \rightarrow t\bar{t}h_3$	210	0.20		

Table 7: Final numbers of signal events for 30 fb^{-1} integrated luminosity at various benchmark points in the LEP hole.

4 Summary and Conclusions

Taking a cue from the frequently discussed possibility of CP -violation in MSSM and its phenomenological consequences at colliders, we explore a popular benchmark scenario (called the CPX scenario) of this broad framework. The study is motivated by recent analyses which reveal that the LEP, in its standard Higgs searches, could not probe some of the region in the parameter space of this scenario having low m_{h_1} and low to moderate $\tan\beta$ values. We concentrated on this ‘unfilled hole’ in the parameter space and studied how well LHC could explore it.

We have found that the associated production of the lightest Higgs boson (which may evade the LEP bound and be as light as 50 GeV or smaller) and two of its ‘light’ mates along with a pair of top quarks and top squarks could be extremely useful in reaching out to this region. This is because one can now exploit modes where the involved couplings and the masses are very characteristic of the CP -violating SUSY scenario. The particular signal we choose for the study is *3-tagged b -jets + dilepton + tagged jets + missing transverse momentum*, the total number of jets being within 5. It is shown that the entire ‘LEP-hole’ can be probed in detail in this final state with less than 50 fb^{-1} of LHC data, and that the CP -violating SUSY effects cannot be faked even by a combined effect from the contending scenarios like CP -conserving MSSM and/or the standard model.

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